A SUMMARY OF SCATTEROMETER RETURNS FROM WATER SURFACES AGITATED BY RAIN

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1. INTRODUCTION

Rain modifies sea-surface roughness, so precautions must be taken to derive accurate surface-winds from scatterometer data obtained in storms. Unbiased wind estimates are needed for oceanic circulation modeling and wave forecasting, which are major subjects areas because of their significant roles in heat flux and gas exchange. For weather and climate studies, it is important to minimize biases due to rain in scatterometer wind data sets. Thus we initiated a research program with the goal of improving the understanding of microwave scattering from rain-roughened seas.

In this paper, we summarize our initial findings from Ka- and Ku-band scatterometers which include: a scaling law for backscattered power as a function of rainrate; a linear superposition model for light rains and low wind speeds; evidence of the importance of scattering from rain-generated ring-waves; and progress towards development of a scattering model for computing normalized radar cross sections from wind and rain roughened water surfaces.

2. METHODOLOGY

We have conducted rain experiments in the NASA wind-wave tank (20 x 1 x 1.2 m) at Wallops Island and in the IMST wind-wave tank (40 x 3 x 2.5 m) at Marseille. Scatterometer data are from Ka- and Ku-band systems like the one described by Bliven and Norcross (1988). The scatterometer data are reported in terms of relative backscattered power (RCS) by using the backscattered power from a metal sphere at the appropriate distance as the normalizing factor. We also built rain simulators: the one at NASA was at 1.5 m above the calm water surface and it produced uniformly sized 2.8 mm diameter water drops that fell from 10 nozzles (35 x 14 cm^2); and the one at IMST was 1 m above the calm water surface and it produced water drops from 72 nozzles (40 x 45 cm^2) distributed among six sizes that generated drops that ranged from 1.2 to 2.8 mm. For a given flow rate, each rain simulator had nearly uniform flow rates through all of its nozzles. Consequently for a given flow rate with the IMST simulator, the drop-size distribution decreases as the drop-size increases - which is like natural rain.

3. RESULTS AND DISCUSSION

3.1 LIGHT RAIN

When a water drop hits a water surface, it can generate a cavity with a crown, which collapses to form a vertical stalk of water, which subsides to spawn rings of gravity-capillary waves that propagate outward (Worthington (1882), Le Méhauté *et al*. (1987) and Le Méhauté (1988)). At incidence angles used from space, a dearth of data hampers validation of numerical models. Atmospheric attenuation and scattering by rain are included in two models that simulate satellite based systems: at nadir by Meneghini and Atlas (1986) and at scatterometer angles by Sobieski *et al*. (1991). Important atmospheric effects have been modeled but the effects of rain on the air-sea interface are less well understood and consequently have yet to be included in remote sensing algorithms.

To examine the relationship between RCS from rain-agitated water surfaces and rainfall rate (R), we simulated light rains (R from 3 to 30 mm/hr) in the NASA and IMST wind-wave tanks (Bliven *et al*. 1993b). All scatterometer data in this summary is from 30° incidence angle with VV polarization. An example of the results from the Ku-band scatterometer is presented in Figure 1 which shows that a linear relationship adequately represents these conditions.

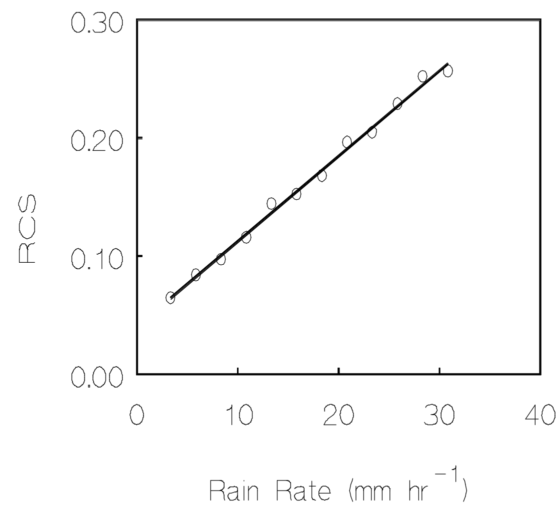

Figure 1 - Ku-band scatterometer (30° incidence angle, vv pol) backscattered power as a function of rain rate in a wave-tank. These data for light rains are well modeled by a linear dependence.

3.2 LIGHT RAIN AND LIGHT WIND

For solely wind forcing, studies by Wu (1969), Banner and Melville (1976) and Melville (1977) provide evidence of dramatic changes in the air-water boundary layers (related to air-flow separation and small-scale wave breaking) such that the momentum exchange is considerably different in light- and high-wind regimes. Those investigators suggested a transitional u_* of approximately 25 cm/s. Scatterometer measurements (Duncan *et al*. 1974, Woiceshyn *et al*. 1986 and Bliven *et al*. 1993a) also show that a regime model is appropriate for relating RCS to the wind and again u_* equal to 25 cm/s is a suitable choice for the transition between light- and high-wind regimes. Therefore to simplify the physical conditions being studied, our investigations commenced with the light-wind regime.

A data set composed of Ka-band RCS measurements for various combinations of light winds and light rains is shown in Figure 2. Notice that either processes can be dominant, depending upon wind and rain conditions, so rain effects on scatterometer wind speed algorithms should not be ignored. Cross sections are typically enhanced by light rain. If rain effects are not accounted for in wind retrieval algorithms, then wind speed estimates are expected to be biased high. Lastly, cross sections at a given wind speed generally increase with greater rainfall, but the relative change decreases as wind speed increases. These features are consistent with Ku-band scatterometer data from laboratory experiments (Moore *et al*. (1979)) and the positive bias (over estimate) of light wind speed estimated due to rain (Black *et al*. (1985)) for Seasat field data.

For light rains and light winds, an additive model (SRWM-1) was proposed by Bliven *et al.* (1993b) in which total radar cross section RCS_T is expressed as

$$RCS_T = RCS_R + RCS_W \qquad (1).$$

Where RCS_R is the average normalized cross-section due to rain-generated roughness and RCS_W is the average due to wind-generated roughness. Even with its simple form, SRWM-1 resolves the principal features of the combined wind and rain data. For example, by expressing SRWM-1 in logarithmic form we obtain

$$\log(RCS_T) = \log(RCS_W) + \log(1+RCS_R/RCS_W) \quad (2).$$

The terms on the right hand side of Equation 2 represent the traditional cross section due to wind plus a positive perturbation due to rain. The magnitude of the rain perturbation scales as a function of wind, i.e., there is an apparent interaction. RCS_W is an increasing function of wind speed, so for a specified rainfall rate, the rain effect decreases as wind speed increases.

The effectiveness of using the SRWM-1 model to estimate winds for combined wind and rain conditions was demonstrated by Bliven *et al.* (1993b) for measurements with the scatterometer pointing not only up-wind, but also at various azimuthal viewing angles. Compared to neglecting rain effects, application of SRWM-1 improves friction velocity estimates for combined light wind and light rain conditions because it greatly reduces large positive biases.

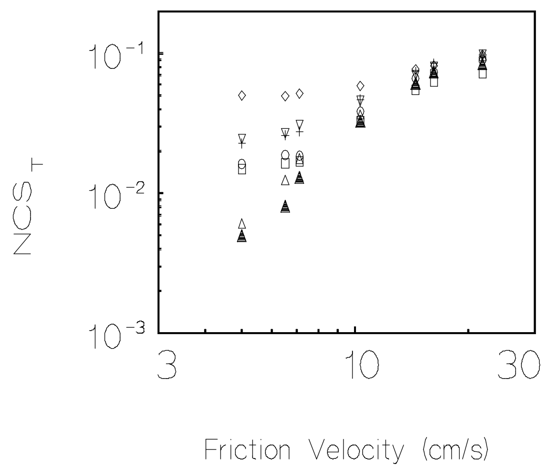

Figure 2 - Scatterometer measurements in the up-wind direction from an air-water interface roughened by light winds and light rains. R (mm/hr) = (>) 0.0, (Î) 2.0, (•) 2.4, (~) 3.1 (%) 6.0, (Ï) 7.5, and (•) 11.3. The relative effect of rain decreases as wind speed increases. If rain effects are neglected, not only do scatterometer wind estimates worsen as rain rates increase but also a positive bias arises.

3.3 SCATTERING FROM RING-WAVES

The component of RCS for rain-agitated water surfaces that is attributable to scattering from ring-waves rather than other features such as stalks and craters has been investigated by Bliven *et al*. (1993c). The analysis consists of a comparison of RCS measurements from solely rain to RCS measurements from solely wind conditions. Surface elevation was measured using a capacitance probe adjacent to the radar footprint on the water surface (just outside of the rain footprint). Ring-waves propagate - but craters and stalks don't. Consequently for the rain cases, the radar measured scattering from all sources but the elevation probe measured only the ring-waves. On the other hand for the solely wind cases, the elevation probe measured wind-generated roughness - for which craters and stalks are not a concern. Since the data comparison shows that RCS is primarily from small-scale features, appropriate scaling factors were used to account for the directional characteristics of short wind-waves (aligned with the wind) and for rain-generated ring-waves (isotropic distribution). Thus we found evidence (Figure 3) that the component of backscattered power attributable to ring-waves is 90% of the backscattered power from the rain-agitated water surface. The 10% residual is ascribed to scattering from other features and to measurement error or uncertainty. This comparison indicates that scattering from ring-waves is the dominant scattering mechanism and it accounts for between 75 and 100% of the backscattered power from rain-agitated water surfaces.

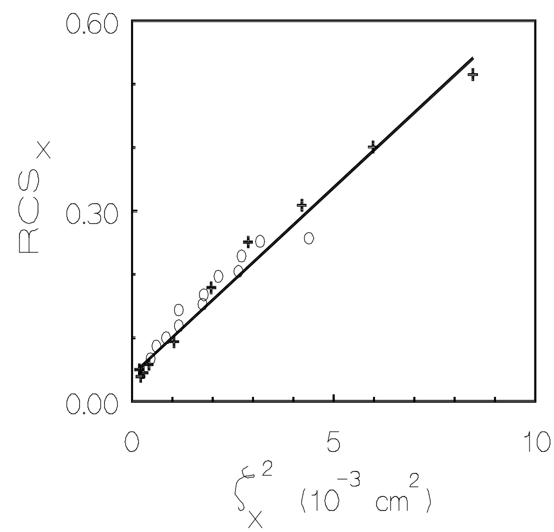

Figure 3- Cross-sections from a Ku-band scatterometer (along-wind, 30° incidence angle, vertical polarization) for solely rain (•) and solely wind (%) as a function of the along wind component of elevation variance ?^{2}. Application of the regression model from the wind conditions indicates that ring-waves are the primary feature contributing to the backscattered power for rainy conditions.

3.4 NUMERICAL MODELING

The results reported herein are being used to enhance the Université Catholique de Louvain UCL composite scattering model, which computes backscattered power values for altimeters and scatterometers by using various sea-surface spectral models. This simulator for wind-roughened seas is amply documented by Guissard *et al.* (1993) and Sobieski *et al.* (1993) and recent developments with respect to rain effects are presented by Sobieski *et al*. (1993).

4. SUMMARY

In this paper, we have summarized our recent efforts to improve the understanding of microwave scattering from water-surfaces roughened by rain. For a more complete understanding, there remains many issues to be clarified. A few examples include improved characterization: of rain generated features (crowns, stalks, ring waves); of effects related to stratification from fresh water layers above sea-water; and of interactions between rain-generated and wind-generated processes. Studies are also needed at higher rainfall rates and with drops at terminal velocity. On the other hand, radar measurements are needed at various incidence angles and polarizations. To systematically investigate many of these topics, the Rain-Sea Interaction Facility was recently established at NASA\GSFC (Bliven and Elfouhaily 1993) and we foresee collaborative studies with investigators who are engaged in measuring and modeling rain-sea interaction processes.

5. Acknowledgment

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